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The Throughput of Wavelength Routing Networks [1]

Richard A. Barry and Pierre A. Humblet
MIT, Laboratory for Information and Decision Systems
Cambridge, MA 02139

1 Introduction

We consider the problem of interconnecting N local area networks (LANs) through a wavelength routing all optical network (λ-routing AON) [1, 2, 3] supporting F wavelengths at R b/s per wavelength. A λ-routing AON is one in which the path of a signal is a function only of the signal wavelength and the origin of the signal. We allow the possibility of wavelength changing so that a signal may arrive at a destination on a different wavelength than it originated on. Furthermore, we assume a slotted system, where each wavelength supports T periodic time slots. A *session*, i.e. connection between a transmitter and a receiver, is assumed to require one frequency-time slot of bandwidth, i.e. R/T b/s.

Each LAN has one outgoing fiber, one incoming fiber, and an unspecified but large number of users. The outgoing (incoming) fiber of a LAN is connected by a broadcast star to all the transmitters (receivers) of that LAN. We assume that there is exactly one active session between each pair of LANs. Therefore the network supports N^2 sessions. Define the *capacity*, C, as the largest value of N^2 possible as a function of F and T.

2 Results

We break the problem into 3 parts. In a *broadcast* network, each receiver hears the signals from each transmitter on each wavelength. Since there is no wavelength re-use, the class of broadcast networks has capacity $C_B = F \cdot T$.

A *light tree* AON (LT-AON) is shown in Fig. 1. Each LAN is connected to up to F trunks on the input and output side and no LAN is connected to more than one trunk on the same wavelength. Note that broadcast networks are a special case of LT-AONs. Light tree networks were first introduced in [4] but "equivalent" networks have been previously studied [6, 7, 8, 9]. Gallager has shown that $C_{LT} = F^2T$ and that the capacity can be achieved without wavelength changing. [5]. The networks which achieve this bound are called Latin Routers (LR) [10]. Equivalent results have been independently derived, see [7, 8].

All other AONs are classified as non-light tree AONs (NLT-AON). An example of a network without a trunk is shown in Fig. 2. NLT-AONs were first studied by Birk in a different context [7]. Birk showed that for $F = 2$, $C_{NLT} \geq O(T \log T)$ beating the F^2T light tree limitation; however no upper bound on C_{NLT} was presented. We show that for any F and T, $C_{NLT} \leq O(F^2T^2)$. By combining Birk's design and the LR, we show that $C_{NLT} \geq O(F^2T \log T)$ for all $F \geq 2$. In addition, for $F \geq T^{1/3}$, $C_{NLT} \geq O(F^2T^{4/3})$. Note that surprisingly, both results are achievable even if $F << T$. None of the NLT-AONs discussed above require wavelength changing.

For a fixed number of wavelengths, F, and a fixed bit rate R per wavelength, increasing T decreases the session bit rate R/T. We study the relationship between session bit rate and maximum network *throughput*, $Z = C * (R/T)$ b/s. Holding F constant, R constant, and varying the number of time slots T, Z_B and Z_{LT} are independent of the session bit rate. However, Z_{NLT} increases as the session rate decreases! This is a fundamental design trade-off that does not exist in traditional multi-access networks.

3 Equivalences

One equivalent model, in terms of connectivity, is to assume F *wavebands* and T wavelengths per waveband. In this model, all wavelengths of a band must be routed together. Implications of this equivalence

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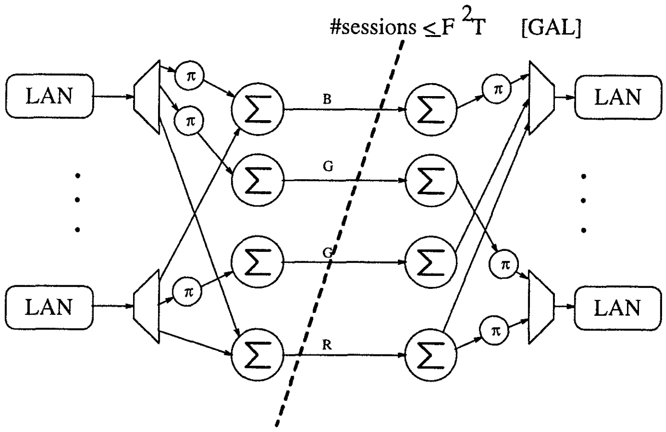


Fig. 1

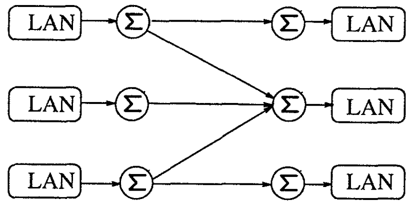
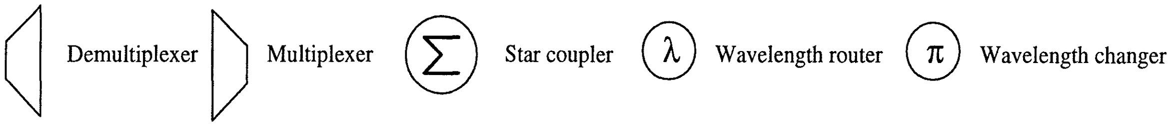


Fig. 2



will be discussed.

We will also discuss the relationship between λ-routing AONs and 4 other types of previously studied networks: two stage switching networks, e.g. [6], networks with multiple transceivers per user [7], non-switching multichannel networks [8], and multiple fiber networks [9]. This provides new insights as well as resolving open issues in all these networks. A general structure for analyzing networks using a combination of the above routing techniques will be presented.

References

[1] M. Goodman, "Multiwavelength networks and new approaches to packet switching," *IEEE Communications Magazine*, vol. 27, pp. 27–35, Oct 1989.

[2] R. Barry and P. Humblet, "On the number of wavelengths needed in WDM networks," LEOS '92, Aug 1992.

[3] R. Barry and P. Humblet, "On the number of wavelengths and switches needed in all optical networks," *To appear in IEEE Trans. on Comm.*, 1993.

[4] S. Alexander, et al, *IEEE Journal of Lightwave Technology*, Special issue on Broadband Optical Networks, May 1993.

[5] R. G. Gallager, *Spatial scalability of B service*, internal memo, July 1992.

[6] N. Pippenger and A. C.-C. Yao, "Rearrangeable networks with limited depth," *SIAM J. Alg. Disc. Meth.*, vol. 3, Dec. 1982.

[7] Y. Birk, N. Linial, and R. Meshulam, "On the uniform-traffic capacity of single-hop interconnections employing shared directional multichannels," *IEEE Trans. on Information Theory*, Jan. 1993, vol. 39, no. 1.

[8] S. C. Liew, *Capacity assignment in non-switching multichannel networks.* PhD thesis, MIT, 1988.

[9] J. Bannister, M. Gerla, and M. Kovačević, "An all-optical multifiber tree network," *IEEE Journal of Lightwave Technology*, Special Issue on Broadband Optical Networks, May 1993.

[10] R. Barry and P. Humblet, "Latin routers, design and implementation," *IEEE Journal of Lightwave Technology*, Special Issue on Broadband Optical Networks, May 1993.